SECONDARY STRIATION DURING FUSE-ELEMENTS DISINTEGRATION

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Abstract: Fuse –element overloaded by currents giving the current density from 5 up to ab 100 kA/mm^2 demonstrate two-stage striated disintegration: primary and secondary. Primary striation is due to magneto-hydrodynamic (MHD) vibration. In course of the primary striation can arise the secondary one. The paper pushes forward two possible mechanisms of the secondary striation: one is "plasma-metal-plasma" model and second "plasma-metal-bridge". For both models an analysis has been given. The conclusion is that "plasma-metal-bridge" model is more realistic one.

I. INTRODUCTION

Striated disintegration of conductors overload by a current has take place if the maximum current density, in the instant of disintegration, is $j_m \approx 5 \div 1000$ kA/mm^2. An analysis of the disintegration, given in [7] based upon experiments [1,2,3,4,9,10,11,12] showed that the fuse-element striation depends on the cross-sectional shape of the conductor, i.e. wire or strip. Hitherto investigation of the striated disintegration, that lasted already many decades, despite many achievements, still generates several controversial views on the physics of phenomena associated and on the value of the disintegration modulus. The modulus given as the simple experimental relations in [4,9,10] are related to the wire or strip dimensions and do not take into account the current density j_m. Meanwhile the paper [7] demonstrate that mentioned module are correct for defined current densities only. Moreover the relations in question are based on observation of the number of fulgurite streaks after finishing of the fuse operation, i.e. they are not related to the changeable number of streaks in course of their formation. The experiments of Arai [1,2] and others stated a dependence of mentioned module during the disintegration process. This observation gave an impulse to introduce [6,7] the term "two stage striated disintegration: primary and secondary". The primary, within small disintegration modulus, is a result of instability of the MHD vibrations of a conductor being in the liquid state. A very complicated MHD model can not be described by some simple formulae on the module, however, it is possible these module to determine using directions given in [6]. One of the conclusion of just quoted paper speaks that the striation can arise in the wires of diameter up to 1 mm and by the current density $j_m \approx 5 \div 1000$ kA/mm^2.

Nevertheless, after some time from arising of a primary disintegration can appear the secondary striation that demonstrate a considerably longer modulus. After suggestions given in [5], the secondary disintegration is a result of joining together in one of the several neighbouring streaks. This phenomenon has take place at relatively small current densities, viz. $j_m \approx 5 \div 100$ kA/mm^2. The upper limit of this zone is approximate only. The reason of it is a minimum time needed to develop the secondary striation. Above mentioned current density there is lack of time to join together the neighbouring streaks. They transform quickly direct into a plasma. Table 1 shows the conditions to get disintegrations and the module of primary and secondary striation.

Table 1 Juxtaposition of experimental and analytical results

Material	Wire diameter [mm]	j_m [kA/mm^2]	Primary modulus of experiments [mm]	Kind of striations	Source	Calculation modulus of primary striation [mm]	Modulus calculated after the formula [7] [mm]
Ag	0.3	8.2	0.31	primary ,secondary	[2]	0.27	1.18
Ag	0.5	6.0	0.36	primary, secondary	[2]	0.38	1.60
Ag	0.5	12.0	0.24	primary, secondary	[1]	0.28	1.60
Cu	0.625	170.0	0.23	primary	[3]	0.22	1.85
Cu	0.625	260.0	0.20	primary	[3]	0.19	1.85

Moreover visible is a good agreement of experiment and calculation.

Up to now there is no attempt to clarify the physics of the secondary disintegration appearance.

The paper gives such an attempt, based on X-ray photography (Fig.1) of a wire striation that shows both primary and secondary striation. There are suggested two possible models why arising the secondary striation.

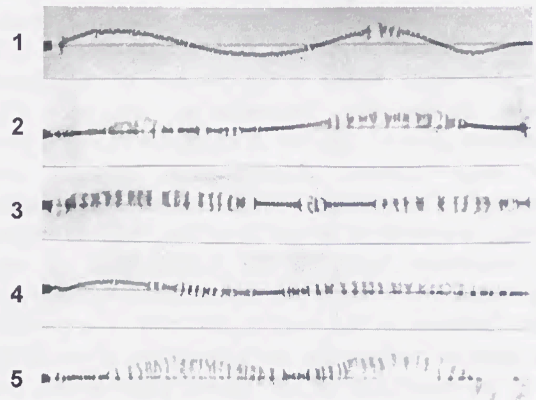

Fig. 1 X-ray photography of consecutive phases of striation disintegration, Ag - wire d = 0.4 mm, l = 50 mm in sand, j_m = 11 kA/mm^2 [1,2]. Pictures shots are taken 1 ms later than disintegration peak voltage. Time distances from that peak are: 1 - 7 μs, 2 - 17 μs, 3 - 21 μs, 4 - 24 μs, 5 - 28 μs

First suggestion pertains to a dynamics of an action on metal primary streak of bothsided plasma layers. This model be called "plasma-metal-plasma model". Second, called "plasma-metal-bridge model" refers to a not simultaneous arising of the wire necks during the primary striation. A most constricted neck will explode at first causing the arc ignition in it. A dynamics of this squash the is due to neighbouring necks behaviour.

II. PRIMARY STRIATION

It was already mentioned that the primary disintegration is due to instability of the MHD vibrations [6,7]. An analysis of such vibrations assumes that in some instant the outer surface of a wire gets the perturbations according to the relations [7]

$$r_p(z,t_0) = R + \sum_{n=1}^{\infty} \delta R_n(t_0) \cos(k_n z + \psi_n) \quad (1)$$

in which: R - radii of wire, t_o - instant of the complete wire liquefaction, r_p (z,t_o) - equation describing of the conductor side surface in instant t_o, $\delta R_n(t_o)$ - disturbance amplitude of wave number k_n in instant t_o, ψ_n – phase of angle of wave number k_n.

Initial perturbations are of small amplitude, of order 1% R. On the evolution of vibrations affect:

- electrodynamics compression of the liquid conductor;
- inertia forces;
- viscosity of metal;
- non-uniform heating, that is larger in the constrictions, causing diminishing of the electric conductivity and enhancing of the metal viscosity.

As a result the speed of evolutions of the perturbations within different wave numbers k_n (1) is different. Highest speed demonstrates a perturbation within number k_{kr} corresponding to the striated disintegration [7]. At the end of evolution, in most overheated parts of metal, it gets lose the thermo-dynamic stability and hence appears a sudden disintegration. Details of the process are given in [6,7]. X-ray photography (Fig. 1) witnesses the non simultaneous wire disintegration.

III. SECONDARY STRIATION

III.1 Plasma – metal – plasma model

Assumed sequence of the events in „plasma-metal-plasma" model is:

- As a result of the current flow arises the primary striation (Fig. 1).
- Individual streaks come to existence not simultaneously. In an early streaks ignites the arc, whereas in neighbouring striates the arcs ignite with some delay (range of μs), however, also not simultaneously.
- After initiation of the arcs there is alternate metal layers divided by plasma ones.
- Dynamic action of the plasma layers (particularly the one which started as first) on the metal layers can make a sudden displacement of the metal and squash of the nearest next plasma layer. As a result the neighbouring metal layers can join together. In this manner can arise the secondary striation (disintegration) modulus of much longer dimension.

In some instant of lasting of the primary striation starts formation of the secondary one. Fig. 2 shows the magnified fragment 3 (Fig. 1) that gets form of the secondary striation.

Process are going extremely fast. In conditions related to Fig. 1 the secondary striation forms within ab 1÷10μs. In this model it is assumed that this disintegration is due to dynamic action of the plasma being on both sides of liquid metal fragment.

Fig. 2 Magnified fragment 3 of X-ray photography (Fig. 1)

In the model it was assumed that the metal layer *k* (Fig. 3) is able to move under influence of the pressure difference (p_1-p_2) of plasma placed on both sides of layer *k*.

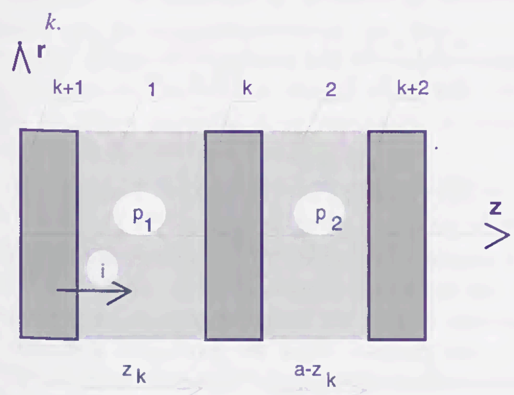

Fig. 3 Sketch of fuse-element fragment assumed in model
1,2 – volume of plasma filling space with z_k and a-z_k and corresponding pressures p_1 i p_2, cross-section A_k

The equation describing displacement of the metal is

$$\frac{m_k}{A_k}\ddot{z}_k = p_1 - p_2 \tag{2}$$

in with: A_k – the cross section of metal.

It is assumed the constant metal mass m_k, despite the fact that each layer vaporises during the disintegration. The assumption justify a very short time of the striated disintegration [6]. Assuming moreover the plasma in volumes *1* and *2* as an ideal gas, its "static" pressure is described by

$$p_l = n_l k T_l \tag{3}$$

where: l=1,2; n_l – density of the particles of their total number N_l in the volume V_l; k – Boltzmann constant, T_l – plasma temperature.

But in reality there is an explosive pressure, not static one [5]. The explosive pressure that arises at very beginning of the explosion, according to [7] can initiate the secondary disintegration by creating some initial speed of the metal layer. This speed can be taken into account by a member of form $\dot{z}_k(t = t_o)$.

The plasma temperature has been determined from a simplified energy equation on the adiabating heating plasma

$$\frac{3}{2}n_l k\frac{dT_l}{dt} = \frac{j_l^2}{\sigma_l} \tag{4}$$

where: j_l - current density in the plasma, σ_l - electrical conductivity of the plasma according to relation

$$\sigma_l = \sigma_{ol}\left(\frac{T_l}{T_{ol}}\right)^{\frac{3}{2}} \tag{5}$$

σ_{ol} – initial plasma conductivity, T_{ol} – plasma temperature in instant t_{ol}.

Integrating the relation (4) including (5), the final relation on the temperature is

$$T_l = T_{ol}\left(1 + \frac{5}{3\sigma_{ol}kn_lT_{ol}}\int_{t_{ol}}^{t} j^2 dt\right)^{\frac{2}{5}} \tag{6}$$

During the fast secondary striation the current and its density is nearly constant. For such assumption and remembering (6) and (3) the relation (2) gets the form

$$\ddot{z}_k = \frac{kA_k}{m_k}\left[\frac{N_1T_{o1}}{A_1z_k}\left(1+\frac{5i^2A_1z_k(t-t_{o1})}{3k\sigma_{o1}N_1T_{o1}}\right)^{\frac{2}{5}} + \right.$$
$$\left. -\frac{N_2T_{o2}}{A_2z_k}\left(1+\frac{5i^2A_2z_k(t-t_{o1})}{3k\sigma_{o2}N_2T_{o1}}\right)^{\frac{2}{5}}\right] = f_1(z_k) \tag{7}$$

A qualitative profile of the function $f_1(z_k)$ is given in Fig. 4.

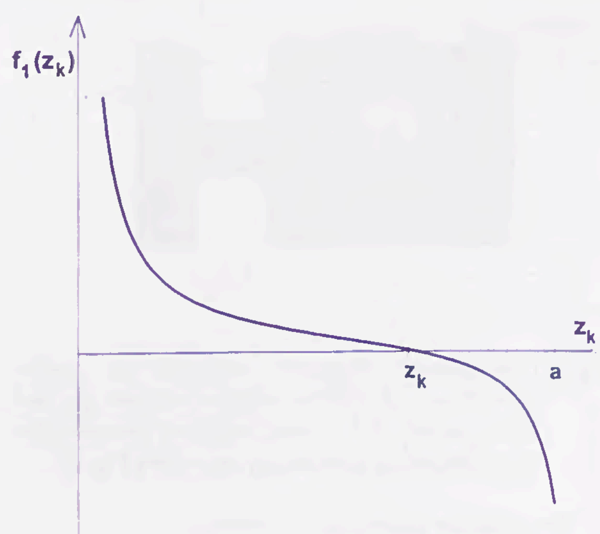

Fig. 4 Qualitative profile of the function $f_1(z_k)$ (7)

From the profile (Fig. 4) outcomes that course of metal layer displacement from one its side arises a decompression of plasma layer and from opposite side, a compression of plasma. In this way arises braking of the metal layer and then a move in opposite direction. It generates a classical vibration system.

Not described in this paper investigations of (7) reveal that the metal layer can vibrate around some equilibrium position.

The probability that the model described has take place is rather small. Author expresses this opinion because the model does not include a very important factor, i.e. an explosive radial ejection of the plasma out of wire cross-section.

III.2 Plasma – metal – bridge model

Assumed sequence of the events in „plasma-metal-bridge" model is nearly this same in "plasma-metal-plasma" model, but there is a substantial difference too. Namely, an arc ignites in one streak so early that in a neighbouring one the current flows through an overheated metal bridge. The plasma pressure (explosive and static [5]) is so high, that before bridge explosion a metal layer gets some move causing absorption of that bridge. In this manner the neighbouring layers are joining together giving a secondary striation within modulus much longer that the primary one.

Fig. 5 illustrates assumed nature of the secondary disintegration according to the model in question. Situation shown lasts a very short time: from an arc ignition in the space *1* up to moment of the bridge *2* disappearance, i.e. up to joining in one of the layers *k* and *k+1* and possibly of be the next nearest metal layers.

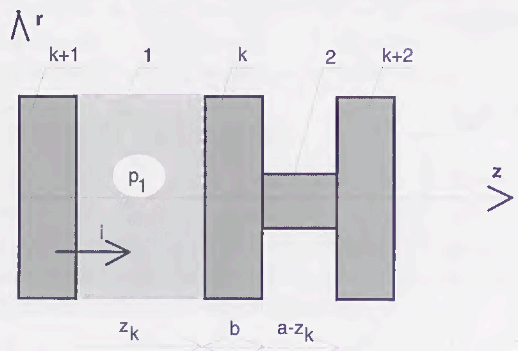

Fig. 5 Fuse-element fragment assumed in model 1- volume of plasma within pressure p_l and cross-section A, 2 – metal bridge of cross-section A_b (outstanding denotations according Fig. 3)

The equation describing this event is

$$\frac{m_k}{A_k}\ddot{z}_k = p_l - p_e - p_h \tag{8}$$

in which: p_l - plasma pressure (3), p_e - explosive pressure [5,13]; p_h - pressure as a result of hydrodynamic resistance, i.e. caused by layer and bridge deformation.

Hydrodynamic pressure can be define by an approximate relation [6]

$$p_h \approx \frac{2\,\nu\,b\,\dot{z}_k}{d^2} \tag{9}$$

where: ν - kinematic viscosity; $d = \sqrt{\frac{4A_b}{\pi}}$ - bridge diameter; $\dot{z}_k$ - velocity of layer displacement.

Introducing (3), (6) and (9) into (8), bearing in mind the assumption identical with taken for (7), one can get

$$\ddot{z}_k = \frac{A_k}{m_k}\left[\frac{k\,N_l T_{ol}}{A_l\,z_k}\left(1+\frac{5i^2 A_l z_k\left(t-t_{ol}\right)}{3\,k\,\sigma_{ol} N_l T_{ol}}\right)^{\frac{2}{5}} - p_e - \frac{2\,\nu\,b\,\dot{z}_k}{d^2}\right] = f_2\left(z_k\right) \tag{10}$$

Of course, the time of layer moving according (10) up to the bridge disappearance (Fig. 5) shall not lasts longer then that to the bridge explosion. A substantial role in the process plays the explosive pressure. Its value is considerably higher than the static one [5,7]. Since explosive pressure lasts a very short time, it can be omitted in (8). This pressure, however, shall be taken into consideration in form of an initial velocity $\dot{z}_k(t = t_{ol})$.

A qualitative profile of the function $f_2(z_k)$ is given in Fig. 6.

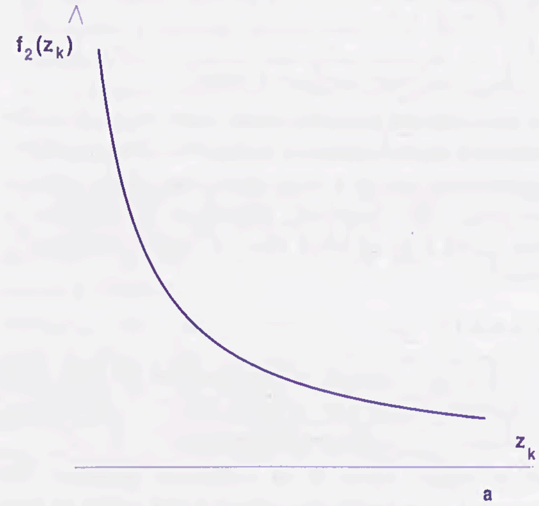

Fig. 6 Qualitative profile of the function $f_2(z_k)$ (10)

From profile (Fig. 6) it is evident that the metal layer that displaces due to plasma pressure and is braked only by a pressure appearing as a result of shape changes of the layer (process of absorption of the bridge by the metal layer). By decompression of the plasma layer it gets smaller, however, a resultant pressure does hot change its direction. Qualitative profile of the function $f_2(z_k)$, given in Fig. 6, shows that the plasma-metal-bridge model is possible.

IV CONCLUSION

Described analysis is of qualitative character. Qualitative analysis of the given equations is a very complicated matter, mainly due to difficulties in determination of the initial conditions and physical parameters. The solutions to the problem considerably depend on the relation between the time in which particular streaks are forming and the relation between the time of the necks and bridges explosion, etc. To reach a proper solution it is necessary to carry out further time consuming investigation.

The positive conclusion from given considerations is that formation of the secondary disintegration, it seems, more probable is the plasma-metal-bridge.

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